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IRAQ'S BOMB: BLUEPRINTS AND ARTIFACTS

By DAVID ALBRIGHT and MARK HIBBS

After more than half a year of investigating Iraq's clandestine nuclear program, U.N. and International Atomic Energy Agency (IAEA) inspectors found the biggest remaining piece of the puzzle: details of Iraq's effort to design and develop a nuclear explosive device. On September 22, an inspection team—the seventh sent by the U.N. Special Commission to uncover Iraq's weapons of mass destruction—discovered the nuclear weapons program archives at program headquarters in Baghdad. Many of the documents found there recorded Iraq's plans and progress.

Less than a week earlier, Rahim Al-Kital, Iraq's ambassador to the IAEA, informed the

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agency's 1991 conference in Vienna that Iraq had already "told the United Nations everything," and that inspectors were "guessing" about a nuclear weapons program that did not exist. But the find put an end to any doubts that Iraq's secret effort to enrich uranium was for weapons purposes.

The documents showed that since 1988 or 1989 Iraq had invested heavily in facilities to develop and make nuclear weapons. By mid-1990, Iraqi scientists had made some progress in understanding how a relatively crude nuclear explosive device with a core of highly enriched uranium would work, and they had done some experiments on parts of the technology. By that time, an experimental program was under way for using shaped conventional charges to activate a nuclear explosion by uniformly compressing a uranium sphere.

But on the eve of the Kuwait invasion, Iraqi experts still had many theoretical and experimental questions to answer. They were also having trouble developing the precision electronic equipment needed in a nuclear weapon—and efforts to obtain the equipment abroad had been thwarted. From evidence of the state of the program contained in the documents, Western experts have deduced that Iraq would probably have needed a year or two to master its weapon design if the Gulf War had not occurred.

An even greater obstacle than weapon design was a shortage of highly enriched uranium. Iraq might have produced enough material for a nuclear weapon in two or three years if the war had not occurred—but it would have been far from certain. After producing enough material for the first weapon, Iraq probably could have produced enough for at least one weapon a year. It therefore could have had a small nuclear arsenal by the middle of the decade, perhaps deliverable by missiles.

The documents

The world saw the showdown in the parking lot of a building in downtown Baghdad [see "Hostages, Headlines, and Hype," page 32], but the papers the hostage inspection team was holding were even more dramatic.

The building where the papers were housed was the headquarters of "Petrochemical Three" (PC-3), Iraq's program to design, test, and develop a nuclear weapon. PC-3 employed several thousand people and was under the control of the Iraqi Atomic Energy Commission. It was also linked to the Defense Ministry and the Ministry of Industry and Military Industrialization. Jaffar Dhia Jaffar, vice-director of the Iraqi commission, has often been portrayed in official accounts as the technical and administrative leader of the nuclear weapons program, but top IAEA officials speculate that Jaffar may not actually have been in charge. Inspectors believe Jaffar headed Iraq's calutron uranium enrichment program, since he has a background in high-energy accelerators. But the Iraqis have taken pains to hide the names of top weapons officials from IAEA inspectors.

U.N. inspectors uncovered a calutron magnet that had been turned on its side and buried in the desert sand.

PHOTOS COURTESY OF THE INTERNATIONAL ATOMIC ENERGY AGENCY

According to David Kay, the IAEA inspection team leader who gained fame in the parking lot episode, Iraqi political authorities began to take great interest in the weapons program after the decision was made, some time in 1988 or 1989, to pour money into the enterprise. On May 7, 1990, the minister of industry and military industrialization opened a site 50 kilometers south of Baghdad called al Atheer that was to be similar to Los Alamos, the primary site where the United States developed the first atomic bombs during World War II. At al Tuwaitha, 20 kilometers southeast of Baghdad, Iraq already had a national nuclear research center, parts of which were subject to IAEA inspections. But beginning in early 1990, personnel, sophisticated equipment, and testing systems relevant to the weapons effort were transferred from Tuwaitha and other sites to al Atheer.

The discovery of Iraq's nuclear archives put an end to any doubts that the secret effort to enrich uranium was for weapons.

The documents found in Baghdad in September detailed Iraqi plans to develop a nuclear explosive device at al Atheer. Few of the papers have been released—particularly sensitive were those revealing connections of foreign companies and individuals with the Iraqi program. But the most concrete information about the program was contained in two progress reports on efforts to design and test an implosion device. The IAEA has released one of these reports, which covers progress made from January 1 to May 31, 1990. Based on this report, interviews with numerous officials, and the seventh—at press time the latest—IAEA inspection report, a fairly detailed picture can be drawn of the state of the Iraqi design program.

Iraq was evidently working hardest on an implosion device [see diagram, page 33]. This type of weapon contains a mass of nuclear material—in this case, highly enriched uranium—at its center. Conventional high explosives around the central mass detonate simultaneously, imploding and compressing the fissile material into a supercritical mass. At that instant, neutrons must be injected into the material to initiate the chain reaction and explosion.

The Iraqi design was relatively crude by modern standards and was taking longer to work out than Western weapon designers would have anticipated. Iraqi scientists had not developed a workable design by the time al Atheer was bombed in early 1991, according to the IAEA. One U.S. weapons laboratory expert said that Iraq would have needed to cover "a lot of

Hostages, headlines, and hype

A year after the U.S. government began fanning speculation about Iraq's bomb capabilities as the Gulf crisis moved toward war, another round of hyperbole on Iraq's nuclear prowess was touched off when Iraq held 44 International Atomic Energy Agency (IAEA) inspectors hostage. Iraqi security forces held the inspectors for 96 hours in a Baghdad parking lot after they had discovered a cache of nuclear weapon documents. IAEA chief inspector David Kay became the center of media attention during the episode, when he held live interviews with the world's major television networks over a satellite-linked telephone.

After intense negotiations the inspectors were freed, and they flew to Bahrain to prepare their report for the IAEA. They also gave interviews to reporters, who then cited them as sources for headline-grabbing revelations about the Iraqi nuclear weapons program.

"U.N. Says Iraq Was Within Months of Nuclear Device," declared the front page of the October 4 *Financial Times*. The London newspaper's Bahrain correspondent wrote that Kay "said Iraq could have been as little as two months away from starting a nuclear arsenal"—assuming that Iraq had a "regular supply of enriched uranium." The *Financial Times* story acknowledged that the enriched uranium bottleneck was a critical one, but it did not elaborate.

Kay backed away from that estimate the next day. At a press conference held by the IAEA in Vienna, he postulated that Iraq's bomb had been 12–18 months away—still a highly optimistic estimate. He later reiterated that estimate at a hearing held by the U.S. Senate Foreign Relations Committee. In repeated interviews and testimony given after the Baghdad documents were found, Kay stressed that Iraq's weapons effort was "highly impressive" and had "considerable breadth."

The October 5 press conference generated more alarming headlines after Kay, IAEA Director General Hans Blix, and other officials hinted that Iraq was on the way to possessing thermonuclear weapons as well, because documents indicated that Iraq had planned to produce lithium 6. According to a *Washington Post* article October 9, while Blix conceded that no lithium 6 had been found in Iraq, "Kay said no other major obstacle appeared to lie in Iraq's path to building a hydrogen bomb except for production of adequate fissile materials and awareness of relevant bomb-design characteristics."

In the absence of any corroborating evidence for an H-bomb program in Iraq, technical officials discreetly backed off the agency's H-bomb story as soon as it was launched. But not before the Bush administration had seized upon Iraq's H-bomb as an argument to retain a scaled-down Star Wars to defend against a future "small" nuclear threat from the Middle East. "For many U.S. officials," Reuters reported in mid-October, "the need for an anti-missile defence was demonstrated by recent revelations that Iraq had been engaged in a massive project to build a hydrogen bomb before the Gulf War."

Another wavelet of speculation was touched off when the media were alerted in late November that the IAEA had found traces of 93 percent enriched uranium unconnected to Iraq's known materials or calutron program. Official and unofficial U.S. sources speculated to reporters that Pakistan or China might have supplied Iraq with a secret and still hidden cache of weapons-grade uranium. Rolf Ekeus, director of the U.N. Special Commission, told the *New York Times* in late November, "The traces seem to imply Iraq had a foreign supplier of highly enriched uranium and that Iraq may still have undeclared stocks." Other officials raised the possibility that unknown Iraqi centrifuge enrichment facilities had produced the 93 percent material.

Buried in the accounts, however, was an equally plausible explanation for the 93 percent material: the samples could have been accidentally contaminated. The analytical procedure, performed at U.S. laboratories, is so sensitive that samples can be contaminated even by highly enriched uranium in dust on the clothing of inspectors, picked up in their own laboratories or facilities. In one case, it is known that a set of samples contained an uranium isotopic mixture that was the same as is found in bits of material from the U.S. National Bureau of Standards used by the IAEA for calibrating instruments and other purposes at its laboratory near Vienna. In another case, however, the range of uranium isotopes did not match any known sources of contamination from the IAEA's laboratory.

The IAEA has collected new samples and has sent them to laboratories in three countries. The sophisticated analyses will take a few months to complete.

Stretching the truth about Iraq's nuclear program is not new for the U.S. administration. But some Western officials, including influential members of the IAEA Board of Governors, say that a few key officials at the IAEA and the United Nations exaggerated their finds to help enlarge their organizations' future mandate to prevent proliferation, and to keep pressure on Iraq to reveal its nuclear secrets. Although the IAEA denies this, one official there admitted, "Our experience has been that, once the Iraqi program is taken off the front pages by crises elsewhere, the Iraqis start denying us information again."

The October 9 *Washington Post* article pointed out that the "disclosure" of Iraq's H-bomb effort "was made as the Security Council considered a draft resolution authorizing long-term monitoring in Iraq to obstruct any revival of the nuclear bomb program." Following up, Kay explained to the Associated Press that Iraq's "nuclear know-how is so sophisticated that it could resume its shattered atomic weapons program unless blocked by constant foreign inspections."

—D.A., M.H

ground" to finish a design by the end of 1992. Although the May 1990 progress report showed that an impressive effort was already under way, most of the text covered work that still needed to be done. According to Theodore Taylor, a former U.S. nuclear weapons designer, the gist of the report was that the "future is much more exciting than the present or past."

Rolf Ekeus, head of the U.N. Special Commission in charge of scrapping Baghdad's weapons of mass destruction, said Iraq had blueprints and considerable knowledge but lagged in engineering.[1] The program had been slowed in part by Iraq's failure to obtain much of the equipment it counted on buying [see "Procurers and Panderers," page 34]. The May report cited four cases in which Iraq had been forced to develop components on its own because they could not be obtained commercially.

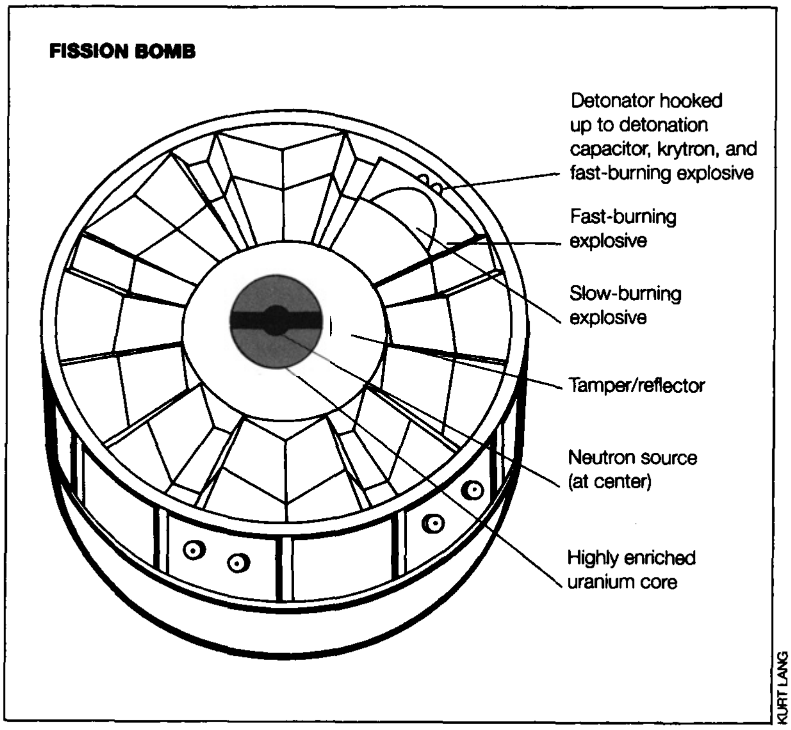
According to Carson Mark, former head of the theoretical division at Los Alamos National Laboratory, the progress report suggests that Iraq had been working on a design of the general type that the United States was developing after 1945. At that time, U.S. efforts concentrated on reducing the size and weight of the implosion-type bomb dropped on Nagasaki. Contrary to conventional wisdom, a country intent on developing nuclear weapons would not need to first build a large, heavy device of the sort dropped on Nagasaki. Nor is it absolutely necessary to conduct a full-scale nuclear explosion of a design to gain confidence that it would work.

A progress report

The January-May 1990 progress report and other sources provide information about Iraq's work in a number of areas essential to developing a bomb:

■ **Theoretical calculations and experiments.** The progress report outlined a broad range of efforts, some quite sophisticated, to carry out the large number of calculations and laboratory and field experiments needed to design a nuclear weapon. An IAEA official said that some of the theoretical work had been going on for a long time. Through extensive searches of the public literature going back to 1945, Iraqi scientists assembled an important compendium of information, including weapons-relevant computer programs and many theoretical and practical studies on high explosives.

According to Iraqi declarations, the theoretical work was being done by the "special tasks" section of PC-3 at Tuwaitha under the direction of Khalid Ibrahim Sa'id. The investigation included theoretical studies of the physical and chemical behavior of materials at high temperatures and pressures, the processes of nuclear fission in an explosion, and theoretical methods to extrapolate laboratory results to the conditions of an actual nuclear explosion—in which the temperatures and pressures would greatly exceed any conditions produced in the laboratory.


FISSION BOMB
Detonator hooked up to detonation capacitor, krytron, and fast-burning explosive
Fast-burning explosive
Slow-burning explosive
Tamper/reflector
Neutron source (at center)
Highly enriched uranium core
KURT LANG

Source: Richard Rhodes, ***The Making of the Atomic Bomb*** (N.Y.: Simon & Schuster, 1988); David Albright.

Theoretical calculations must accurately predict experimental results. The progress report included many examples of successful and unsuccessful attempts to develop theoretical models and to verify the models' predictions. It indicated that much work remained. In important cases, calculations did not fit what was observed experimentally, and in others, experiments could not yet be done. What is more, work was just beginning on understanding the spherical geometry of an implosion system—a particularly challenging task.

According to Mark, the information contained in the January-May 1990 progress report indicated that Iraq would have needed at least a year, working at a fast pace, to complete the design work on a bomb. He added, however, that any such estimates are fraught with uncertainty. An experienced weapon designer can anticipate many of the problems the Iraqis would have faced in designing their weapon. But it is impossible to know whether the Iraqis were prepared to deal with these problems.

The report indicated that Iraq was not ready to select an actual design with a specific amount of highly enriched uranium, high explosives, and tamper. Nevertheless, the progress report for the last half of 1989—which the IAEA obtained but has not released—gives specific information about the type of device Iraq was exploring. One inspector said that the Iraqi scientists were planning a device with a solid core of about 18 kilograms of weapon-grade uranium; a reflector of natural uranium metal a few centimeters

Procurers and panderers

Baghdad's effort to buy equipment and know-how abroad remains by far the most sensitive aspect of the secret nuclear weapons program. Despite Iraqi lies and subterfuges—labels were removed from much of the equipment before inspectors arrived—the IAEA has compiled comprehensive details of equipment known to have been imported. Western centrifuge experts taken to Iraq have identified the manufacturers of much of the disguised equipment. But important questions remain about how the transfer of technology occurred. The public has learned little about Iraq's procurement efforts. Western companies and their governments have pressured U.N. agencies to suppress information that might point to them as sources of the technology. Some officials are also concerned that a premature disclosure of procurement details might enable some companies and individuals to cover their tracks.

Most of the information assembled through inspections and by examining the Baghdad documents details relatively common items Iraq purchased for its nuclear program. But a few key items on the list may provide valuable leads as to where Iraq got equipment and technology that was directly related to nuclear weapons.

Instead of releasing such information publicly last fall, however, the U.N. Special Commission divided it into discrete lists for the countries involved, giving each government only information concerning firms in its jurisdiction. Western officials said some information was suppressed after the fifth IAEA inspection, under pressure from the British-Dutch-German Urenco enrichment consortium, whose technology apparently served as the backbone of Iraq's centrifuge program. And after IAEA inspectors returned from the seventh inspection in October, company-specific procurement information was kept out of the 60-page final report.

The information blockage has bought time for suspect firms. Bracing for anticipated leaks, nervous companies on the list provided to one European government attempted to coordinate their damage-control efforts. At the conclusion of a meeting held in mid-November, the firms vowed to fight hard against expected media reports linking their commercial activities to the Iraqi nuclear program.

Not surprisingly, firms have balked at admitting their involvement. The German firm Interatom GmbH steadfastly denied for a year that it had even unwittingly contributed to Iraq's nuclear program. But by November, IAEA inspectors were confident that Siemens subsidiary Interatom and a German construction firm, Strabag AG, had been at work on a building at al Furat in which Iraq planned to house a 100-machine pilot centrifuge cascade hall.

While U.N. bodies kept the lid on procurement details, some information—by no means the most significant—has come out through parallel official sources. In September, for example, the French government told the IAEA in confidence that it had provided Iraq with three metric tons of heavy water at the time it sent the Osirak reactor—the reactor Israel bombed in 1981. The IAEA refused to reveal the source of the water, but other informed officials were willing to do so.

That lesson has not been lost on the United Nations, the IAEA, and member governments. On December 11, the IAEA named 13 companies whose equipment had been found in Iraq. But this is only the tip of the iceberg. Much more equipment and technology from unnamed companies—including unfinished calutron magnets made in Germany—had been shipped to Iraq.

—D.A., M.H.

thick; and a tamper of hardened iron, also a few centimeters thick. A device of this type could weigh less than 500 kilograms and could have an outer diameter of 50–70 centimeters—significantly smaller and lighter than the devices developed in the Manhattan Project, which weighed many tons.

■ **Levitation.** One set of principles that can make a significantly lighter bomb is "levitation," which often involves placing a spherically symmetric empty space beneath the layer of high explosives—thus increasing the power of the implosion. A simple system would put an air gap between the reflector and the core, and the heavy shell would accelerate before hitting the core, increasing the core's compression. Since a levitated design uses the high explosives more efficiently, the design can achieve the same nuclear explosion with less uranium or high explosive.

There is some evidence in the January-May 1990 report that Iraq was planning to study levitation, although Iraqi officials have denied this. Mark said that the May progress report indicated that Iraq was "not close enough to have decided whether levitation was a good idea." He added that scientists would first have had to complete work on understanding implosion systems but then might have decided to incorporate levitation in a design.

■ **Shaped charges and implosion package testing.** The conventional high explosives that surround the tamper and core in an implosion system must be precisely shaped and placed to generate spherical shock waves. Iraq had undertaken theoretical and experimental programs to understand how shaped charges work and are made but, according to an IAEA official, it had not yet tested such charges. Twenty tests had been conducted at the Hatteen Establishment, which is located next to al Atheer and contains a high-explosive test bunker. But the tests appear to have been limited to generating planar shock waves.

According to the January-May 1990 progress report, these tests were aimed at understanding how to produce homogeneous shock waves, and "some encouraging results were achieved in this area." Many additional, repetitive tests would have been required to develop shaped charges and an implosion package.

A possible test site for the entire implosion system was al Hadre, located 200 kilometers northwest of Baghdad. An open firing range for fuel-air bombs and fragmentation testing, this site was believed by the seventh inspection team to have been suitable for such tests. To conduct the tests, Iraq would have needed special testing equipment to determine the uniformity of compressions achieved in the nuclear core. Iraq already possessed high-speed cameras at Baghdad University that could capture images within 0.1 nanosecond. The progress report also described efforts to make a 600-kilovolt flash X-ray machine to provide a profile of a mock core used in an implosion test. The X-rays would have had sufficient energy to show whether the core was being imploded uniformly or whether core material was squirting out.

Iraq had imported hundreds of tons of HMX, which is the most desirable conventional explosive for nuclear weapons. The material was also used in aerial bombs, but at the end of the Gulf War, Iraq still had 250 tons of it—more than enough to supply a small nuclear arsenal—stored at al QaQaa, the military research and development facility 40 kilometers northwest of Baghdad. According to the May 1990 progress report, Iraq had been installing hot and cold isostatic presses at al Atheer suitable for making shaped charges.

■ **Neutron initiators.** At the moment of compression, neutrons must be injected into the highly enriched uranium core to start the chain reaction. Iraq was developing beryllium-polonium neutron initiators, which, in an implosion system, are typically about the size of a marble and placed at the very center of the device. These initiators are usually made from concentric spheres of polonium 210 and beryllium, separated by a thin layer of material to shield the beryllium from the alpha particles produced by the radioactive decay of polonium 210. When the shock wave from the high explosives hits the initiator, it crushes the beryllium and polonium together, producing large amounts of neutrons.

This type of initiator presents several difficult challenges, since the two materials must be mixed thoroughly at the right instant. Manhattan Project scientists invented and tested many designs before a satisfactory one was selected. Iraq was still apparently working on developing this type of initiator. It had tested some models using high-explosive lenses, according to the January-May 1990 progress report, but no details were provided.

Because it decays rapidly, polonium 210 must be produced continually if a nuclear arsenal is to be maintained, and therefore Iraq was also investigating external neutron initiators. These work by fusing small amounts of tritium and deuterium, producing a spurt of neutrons that penetrates the core and initiates the chain reaction. Iraq appears to have aimed for one of the more difficult of such designs (a "dense plasma focusing" system), without getting very far.

■ **Electronic systems for triggering.** A great deal of high-performance electronic equipment is needed to set off the shaped charges simultaneously—or at least within a fraction of a microsecond. Commerce in such equipment is controlled by U.S. and European export lists, and Iraq's efforts to acquire it abroad had been thwarted [see March 1991 *Bulletin*]. Iraq appears, therefore, to have been developing its own crude triggering system incorporating a few dozen bridgewires (detonators) connected to a detonation capacitor, which stores large amounts of electrical energy. The energy is released to the bridgewires by a high-speed electronic switch that works within a fraction of a microsecond. The capacitor would be charged by miniaturized power supplies weighing half a kilogram.

The seventh inspection report said, "In general, the results of the IAEA inspections suggest that the local capabilities in electronics were not on a par with the competence in metallurgy, chemistry, and detonics." It concluded that the capacitors made at Tuwaitha did not seem adequate for the triggering system being considered. According to Iraqi declarations, the multiple bridgewire sets being developed at al QaQaa had not come closer than half a microsecond to simultaneity. Better synchronization is desired to insure uniform compressions in the implosion system.

According to the progress report, Iraq had been able to upgrade about 150 lower-quality capacitors, which it had obtained from Maxwell Electronics in California in 1989. It is not known whether these upgraded systems were good enough for a triggering system.

Because Iraq had been unable to buy high-speed krytrons—a particular type of switch that is very good but hard to get—it was developing more primitive junction switches that used a spark gap. William Higinbotham, who headed the electronics group at Los Alamos during the Manhattan Project, says that it is difficult to trigger spark gaps quickly enough for weapons purposes.

Iraq was developing an infrastructure to produce specialized electronics components for nuclear weapons at Tuwaitha and al QaQaa. Most experts believe that in time Iraq would have overcome the difficulties and produced adequate electronic equipment for nuclear weapons.

■ **Other infrastructure.** The Soviet-supplied IRT-5000 **research reactor**, which was safeguarded by the IAEA, was nevertheless an important part of the weapons program. The reactor had produced polonium 210, essential for the internal neutron initiators, by irradiating bismuth, although it is unclear whether Iraq could have secretly produced enough polonium for a nuclear arsenal over the long term in this reactor. The reactor also produced small quantities of plutonium 238. Although the progress report does not say what the plutonium was for, it could have been used for neutron initiator research and development in place of short-lived polonium 210.

An IAEA inspector said that Iraq was believed capable of producing **uranium metal**

Most experts believe that in time Iraq would have overcome its difficulties with electronic components.

Evidence suggests that Iraq was several years away from developing a missile that could hold a nuclear warhead.

18–24 months before the invasion of Kuwait. Metallurgy skills were developed at al Tuwaitha, ostensibly to make uranium-tipped (non-nuclear) shells that could penetrate armor. Iraqi officials admit that about 1,000 kilograms of uranium metal was produced at Tuwaitha. About a fourth of this was cast, in furnaces, into solid metal shapes. Casting uranium metal is a necessary step in making bomb components. A semi-industrial uranium metal production capability was being developed at al Atheer.

Questions remain about Iraq's ability to **machine weapons components** out of highly enriched uranium to high enough standards of smoothness and uniformity. According to the January-May 1990 report, Iraq was using the results of its experiments with natural uranium to begin developing the capability to make highly enriched uranium metal components, but little information has been found that indicates Iraq's ability to produce high-quality bomb components.

A number of experiments aimed at chemically purifying highly enriched uranium were also performed, and systems were being built for purifying the uranium. If the concentrations of trace impurities such as boron and oxygen are not reduced in the uranium, these impurities can interact with alpha particles from uranium's radioactive decay, producing significant numbers of neutrons that would increase the probability of a premature chain reaction.

■ **Weaponization.** There has been no definitive information about whether Iraq intended to make bombs, although it has several aircraft that could deliver nuclear bombs. Making a bomb is easier than making a missile warhead, however, which Iraq may have intended to do—although no direct evidence has been found indicating either this intention or any progress on such a project.

According to the preliminary sixth inspection report—a final one was never released—what IAEA inspectors found was a document "suggesting the parallel development of a missile delivery system for the ongoing nuclear weapons program. In the document, the Ministry of Defense instructed the Iraqi Atomic Energy Commission to postpone an experiment until after surface-to-surface missile testing."

But information about Iraqi attempts to put chemical warheads on modified Soviet-made Scud missiles raises questions about whether Iraq would have succeeded in developing nuclear-tipped missiles. A Soviet expert "just shook his head," according to an Associated Press report, when he looked at the primitive technology used to modify the Scuds to hold chemical warheads.[2] Some experts who inspected the missiles thought that if they had been fired, the warheads would have been destroyed by heat upon reentry into the atmosphere.[3] Others believed that the chemical warheads, which were only partially filled, probably would have destabilized the missiles, causing them to swerve off course. Inspectors have been unable to find any evidence that the chemical-tipped Scuds had ever been tested.

Components of a nuclear warhead require great protection from gravity forces and other stresses during flight. Available evidence suggests that Iraq was several years away from developing a missile that could hold a nuclear warhead.

Other designs?

Some IAEA inspectors suspect that Iraq had already designed a gun-type device, although they have uncovered no direct evidence of such a program; they believe that the main effort focused on an implosion system. A gun-type device (the kind that was used over Hiroshima) achieves supercriticality by firing one slug of weapon-grade uranium down a tube into another piece that is surrounded by a neutron reflector/tamper. Although it is somewhat simpler to execute than an implosion design, it requires significantly more weapon-grade uranium, which typically makes the weapon bulkier.

Last summer, while Iraq was still denying it had a weapons program, Jaffar, the titular head of the program, told inspectors that Iraq had no interest in a crude gun-type device and would have preferred an implosion weapon. Nevertheless, there are two indirect indications that Iraq was working on such a device, inspectors said. First, one of the neutron initiator models appeared better suited for this design than for an implosion design. A second indication was that Iraq was installing a production capability to make tungsten carbide, which is a good reflector/tamper in a gun-type bomb, at al Atheer.

In any case, a gun device presents demanding mechanical challenges. A barrel must be developed that can withstand the firing of a high-density uranium plug, which is about 10 times as dense as a normal artillery shell and therefore generates 10 times as much pressure on the barrel breech. The plug must be fired so that it seats properly into the main components of the device at the other end of the barrel without destroying them or going out the end. Solving this problem required a significant amount of time in the Manhattan Project. These mechanical engineering steps would have required six or more successful test shots using natural uranium metal, according to Mark.

Although available evidence shows that Iraq was concentrating on developing relatively crude nuclear explosive devices, some information, such as the indication that levitation might have been considered, suggests that Iraq may have been planning to develop more advanced designs for the future. But more advanced designs, such as hydrogen bombs or tritium-boosted atomic bombs, would have remained out of Iraq's reach for a long time.

The only indication of possible intent to acquire such weapons is that Iraq had a declared capability to produce small quantities of lithium 6 at Tuwaitha, and it planned to install a larger capability. Lithium 6 can be used in civilian fusion research, but Iraq did not have such a program. It can be irradiated in a reactor to produce tritium for boosted weapons, but Iraq's largest reactor, the IRT-5000, would not have been large enough to produce much tritium. Lithium 6 can also be used in H-bombs. Taylor, the former weapons designer, believes that Iraq may have begun theoretical exploration of H-bombs and boosting. Some of the more sophisticated computer programs Iraq was developing might have been useful in solving problems encountered in boosting.

On the other hand, Iraq may have produced the lithium simply because it was able to do so and because the material might have been useful later. Lithium 6 is relatively easy to make.

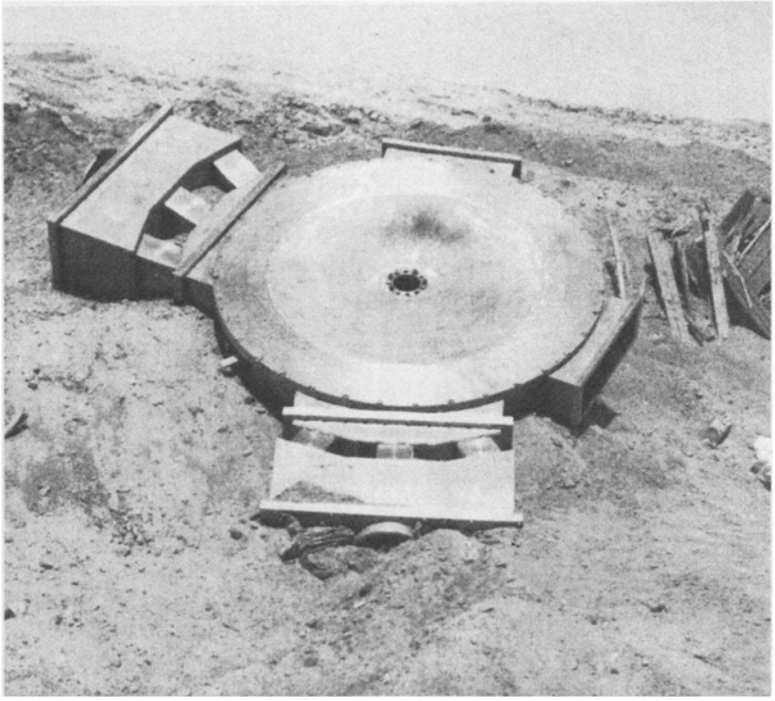
Highly enriched uranium

The calutron program, Iraq's primary route to highly enriched uranium, received little media attention in the past few months as attention shifted to documents on Iraq's program to develop nuclear weapons. But optimistic assumptions about how well the calutron program would work were behind the public estimates by IAEA and U.N. officials that Iraq was 12–18 months from being able to produce an atom bomb.

These assumptions glossed over findings that Iraq had managed to produce only milligram quantities of highly enriched uranium. The estimates were based on the assumption that the transition from pilot-scale production to industrial scale would have been rapid and seamless.

We reported in the October 1991 *Bulletin* that during 1990 Iraq was test-operating eight "alpha" calutrons for production of low-enriched uranium. The machines were installed at Tarmiya, 40 kilometers northwest of Baghdad, between February and September 1990 and operated at declared average capacities of 15 percent. An IAEA inspector said that although Tarmiya had been planned as a major production site, it was functioning as an advanced research and development facility for calutrons at the time of the bombing in January 1991. Iraq was then in the process of installing 17 other alpha machines, although all the components for them had not been manufactured. A total of 70 alpha machines was planned.

The low-enriched uranium produced in the alpha machines would have been enriched further, to weapon grade, in 20 "beta" machines, six of which were under construction when Tarmiya was bombed. None of these had been installed at the time of the bombing.

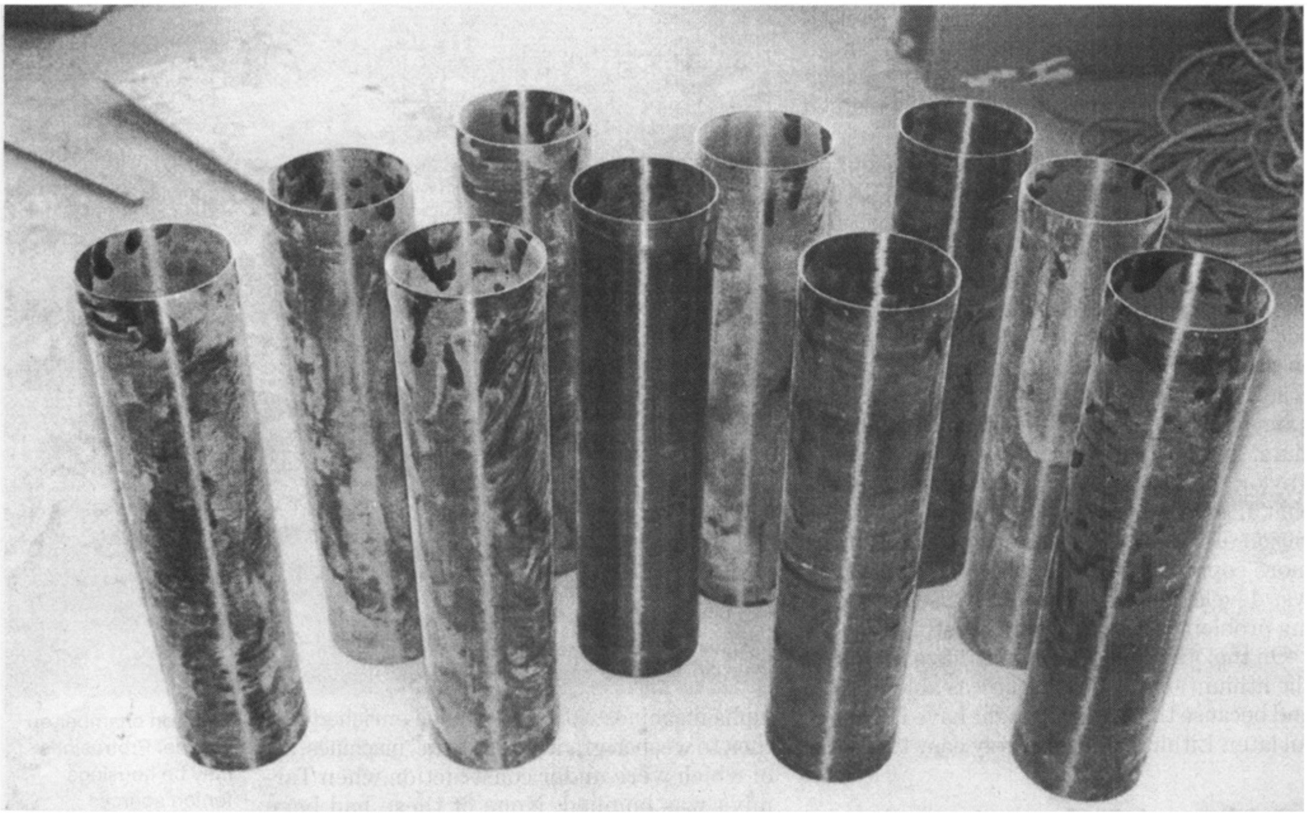


Calutron chamber on its side. Protrusions may be housings for ion sources and collectors.

Iraq was building a similar facility at al Sharqat, 200 kilometers northwest of Baghdad, which was 80–90 percent complete when it was bombed. According to an IAEA official, Iraqis said a decision had been made in mid-1989 not to finish this facility because it had been intended as a backup to Tarmiya, which was vulnerable to bombing during the war with Iran. But the seventh inspection team found some evidence of construction after the decision to cancel it had supposedly been made. In any event, no calutrons had been installed there.

In making their optimistic uranium-enrichment estimates, an IAEA official said they assumed that each alpha machine would operate at full output an average of 55 percent of the year and thus, using natural uranium as feedstock, could produce on average 150–200 grams of uranium 235 a year. This would supply enough low-enriched uranium for the eventual production, in the beta machines, of 11–15 kilograms of weapon-grade uranium a year—clearly enough for a bomb's worth every two years.

The fourth inspection report said that the calutrons had incorporated modern accelerator technology that had been unavailable to the Manhattan Project and that the Iraqis had designed the calutrons to allow the collectors and stainless steel liners to be replaced rapidly, shortening shutdown time. The report said that the alpha machine capacity might, therefore, have been increased significantly, once operating experience had been gained. In the most



Rotor tubes for gas centrifuges. Darker ones are imported carbon-fiber tubes. Mottled ones were made in Iraq of maraging steel.

optimistic projection—that is, operating at full capacity all the time—output would rise to as high as 20–27 kilograms of weapon-grade uranium a year.

One controversial assumption for the above estimates was that each ion beam current in an alpha calutron would reach its design goal of 150 milliamps—a total of 600 milliamps per machine, since each had four ion sources. Experts differ on whether Iraq could have operated the calutrons at 600 milliamps. Currents this high were achieved in the Manhattan Project calutrons, although more typical values were 100 milliamps per source. The inspector in charge of developing the estimates said that a machine would have reached 400 milliamps pretty quickly but would have taken about a year longer to reach 600 milliamps. Other experts doubted that the design beam current could have been maintained on a sustained basis. One expert said he thought 600 milliamps was optimistic, at the "best end of things," and that 400 milliamps would have been a more realistic estimate of average performance. Under this latter assumption, the plant could not have produced more than 18 kilograms a year of highly enriched uranium, operating at full capacity and using natural uranium feed.

The biggest unknown is how long it would have taken Iraq to reach industrial-scale operation. The transition from prototype calutron operation to industrial production can be difficult. The fourth inspection report said: "It is possible—but by no means certain—that full production operation at Tarmiya might not have been achieved for another 18–36 months." Iraqis cited major problems in producing uranium tetrachloride feedstock and in supplying graphite for the collectors. The fourth report also stated that "there may have been human resource problems associated with these large facilities." In other words, it might have been hard to find enough skilled personnel to produce, install, and operate calutron and associated chemical separation facilities.

Yet one IAEA official put it "within the realm of possibility" that Iraq could have built and installed enough machines in time to produce enough material for a nuclear device within a year—if the program had not been interrupted. Most experts interviewed for this article disagreed. One inspector said it might have been possible if no difficulties were encountered in installation and scale-up, and if the design of the bomb required less material than evidence showed.

The same inspector said that producing enough material for a bomb "could easily have stretched out to three years." He said that Iraq would probably have required a year just to get all the units running. During the next year, with the calutrons operating about half the time and at less than maximum currents, Iraq might have produced about 10 kilograms of weapon-grade uranium. Then, beginning in 1993, output might have been increased by keeping the machines operating something closer to 100 percent of the time and with higher beam currents.

Iraq had a stock of about 1,800 kilograms of safeguarded low-enriched uranium which it might have diverted to produce weapon material, but this would have supplied only about enough for one or two bombs. IAEA safeguards would probably have detected the diversion, perhaps blowing the cover of the entire clandestine enrichment program. There is no evidence that Iraq possessed unsafeguarded low-enriched uranium.

Centrifuges

Recent closer examination of Iraq's gas centrifuge program—another possible route to uranium enrichment—indicates that it, too, faced serious problems in the move from laboratory testing to industrial production. Recent information also confirms that the program depended heavily on foreign assistance. So far, the inspectors have only identified major supplier companies and say they have not yet learned conclusively the names of Western individuals or companies who provided detailed technical information about centrifuges.

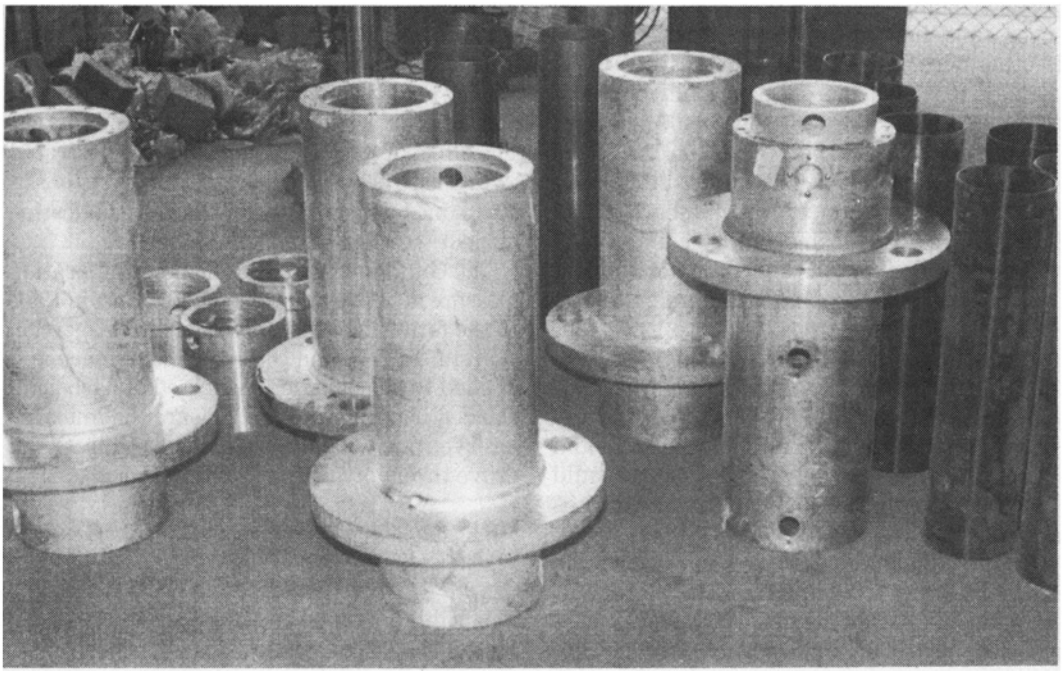
The fourth IAEA inspection report notes that "Iraq's scientific understanding was still limited, with test work only just beginning." Between mid-1988 and late 1990, Iraqi officials said, only single machine tests had been conducted (centrifuges must eventually be linked together in "cascades"), and only minute quantities of uranium had been enriched. Iraq was operating two test stands, one for mechanical tests of centrifuge components and another for process tests using a closed loop of uranium hexafluoride gas. Two centrifuges, using rotors made of carbon-fiber composite materials, had been successfully used in these stands. The process test stand had enriched tiny amounts of uranium, although the rotor used in it broke down and was badly damaged.

Inspectors do not believe that Iraq was capable of manufacturing carbon-fiber rotors of quality high enough to enrich uranium. They believe that the 10 carbon-fiber rotors shown to them may have been based on a design by Urenco, the European enrichment consortium. The fibers are known to have been bought in Japan, and the rotors are believed to have been manufactured outside Iraq. According to one inspector, the rotor featured no inner aluminum liner, an indication that they were of a more advanced type able to resist corrosive uranium hexafluoride. The rotors were able to spin at a top speed of only 60,000 revolutions per minute (450 meters per second at the outer wall). It is possible to manufacture carbon-fiber rotors with superior materials that allow for considerably higher speeds.

Because exporting carbon-fiber rotors violates restrictions in most supplier countries, Iraq would have found it difficult to import all of the key components for the thousands of centrifuges needed for an enrichment program. It would have had to learn to make them on its own, a technically daunting prospect.

According to information compiled by inspectors to date, the Iraqi carbon-fiber centrifuge was based on the fourth Urenco centrifuge for which Iraq had obtained classified design information. The three other designs—G-1, a first-generation centrifuge designed in Germany, and its two more advanced successors, G-2 and G-3—used rotors manufactured from maraging steel, a specialty metal able to withstand high centrifu-

Iraq's gas centrifuge program depended heavily on foreign assistance.



Housings and other centrifuge parts.

Money was no object and many activities were pursued simultaneously.

gal forces. It is made by only a few countries.

At the outset of the Gulf War, Iraq was apparently poised to put together a facility, codenamed al Furat, for large-scale production of a G-1-type centrifuge manufactured from maraging steel and featuring design modifications from G-2 and G-3. At several sites, Iraq had made small numbers of some components for this centrifuge—outer casings, molecular pumps, and bottom bearings [see March 1991 *Bulletin* for a description of centrifuge technology]. A limited number of components, including maraging steel rotor tubes, were made at al Furat during the last few months of 1990, although the facility was far from complete. Experts who examined maraging steel rotors shown to IAEA inspectors during the fourth inspection, however, corroborated Iraqi statements that the rotors were of insufficient quality to use for enriching uranium.

To date, moreover, inspectors have found no significant supply of maraging steel in Iraq, nor any indication of large-scale purchases of this metal abroad. Yet Iraq apparently intended to progress directly from manufacturing a small number of poor-quality rotors to producing hundreds of centrifuges a year. It planned initially to produce 200 usable centrifuges a year, which would have meant making at least three or four times that number in the early phase of component production. Centrifuges must be manufactured to such high quality that most end up being rejected, particularly in an inexperienced manufacturing operation.

Iraqi experts said they intended to begin operation of a 100-machine cascade at al Furat in mid-1993 and a 500-machine cascade at an unknown location by early 1996. This schedule must be viewed with some skepticism, in the absence of any evidence that Iraq could have successfully built and operated a small cascade. In other nuclear programs, small cascades with perhaps 10–15 machines are normally built and operated before larger cascades of 100 machines or more are constructed.

Another possibility is that unrealistic and premature plans to produce large numbers of centrifuges were set in motion by competition between rival teams working on different clandestine routes to enriching uranium.

Recent investigations by customs intelligence officials indicate that Iraq had tried, apparently unsuccessfully, to acquire aluminum tubing manufactured to centrifuge specifications from firms in Switzerland and Germany. The amounts being sought would have been enough to connect the centrifuges in both cascades.

If Iraq could have obtained maraging steel and learned how to work with it, the IAEA stated, "the plan set for the mid-1990s would most probably have been achieved." Even so, however, a 100-machine cascade of G-1-type centrifuges, working fully and on schedule, could have produced at most about 4 kilograms of weapon-grade uranium by the end of 1995—about one-fifth the amount needed for a nuclear bomb. To make 20 kilograms a year, Iraq would have needed to operate roughly 1,500 centrifuges at optimum levels.

Dig deeper, look closer

Estimating precisely when Iraq would have had its first bomb is difficult in part because of the way Iraq's nuclear effort was organized. Because money was no object, many activities were pursued simultaneously. Some involved research and development; others were geared to setting up production facilities even before the research bore fruit. When these efforts would have converged into a successful nuclear weapons production program is difficult to predict. Nevertheless, it is clear that by the mid-1990s Iraq could well have emerged with a small nuclear arsenal that would have fundamentally changed the Middle East.

Iraqi nuclear experts remain at large, and their knowledge is intact. To insure that Iraq does not resume the quest for nuclear weapons, the country must be monitored over the long term, and controls over the transfer of related technology and equipment must be improved. Western export controls were becoming more effective shortly before the war broke out, but only the full embargo, imposed after Iraq invaded Kuwait, fully prevented Iraq from getting key equipment for uranium enrichment and weapons development. Still, Iraq had been able secretly to develop calutrons, a technology not covered by export controls.

As the IAEA begins long-term monitoring, it will require continued access to intelligence information from member governments. The agency must also retain the backing of the U.N. Security Council to gain access to Iraqi facilities. The effort of the past months has demonstrated that, with international cooperation, it is possible to uncover even a deeply buried clandestine nuclear weapons program.

The Gulf War served as the nonproliferation measure of last resort in the Middle East in 1991. In the future, a more comprehensive inspection system, modeled on the Iraqi experience and applied to all countries suspected of harboring clandestine programs, may insure that military intervention will not be needed to address the grave threat of nuclear proliferation. ■

1. Reuters News Service, "U.N. Gives Iraq Deadline on Queries for Dual-Use Industries," Nov. 12, 1991.
2. Associated Press, "Iraq-Chemical Weapons," Nov. 12, 1991.
3. John Tagliabue, "U.N. Finds Toxic-Tipped Scuds," *International Herald Tribune*, Nov. 12, 1991, p. 6.